

Fast prototyping of high-aspect ratio, high-resolution X-ray masks by gas-assisted focused ion beam

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Abstract

The capacity of chemically-assisted Focused Ion Beam (**FIB**) etching systems to **undertake** direct and highly anisotropic erosion of thin and thick gold (or other high atomic number {Z}) coatings on X-ray mask membranes/substrates provides new levels of precision, flexibility, simplification and rapidity in the manufacture of mask absorber patterns, allowing for fast prototyping of high-aspect ratio, high-resolution masks for deep X-ray lithography. In preliminary demonstrations of an automated FIB system operating at 30 keV with a gallium liquid metal source and an iodine gas injection system illustrated the capability of the technique for direct milling into a few micrometer thick gold. Focused ion beam diameters as small as 7nm were obtained, enabling fabrication well into the sub-hundred nanometer regime.

1. Introduction and motivation for the work

An X-ray mask is generally a composite structure consisting of a membrane of low Z material which acts as a mechanical support (membrane or bulk material) for X-ray absorbing microstructures of high Z-material (gold, tungsten, tantalum, etc.) and which is X-ray transmissive at the wavelength of interest. Depending upon the energy of the X-rays and the height of resist microstructures that need to be produced, the thickness of the mask absorber structures varies between a few tenths of microns for thin resist for microelectronic applications to tens of microns for very hard X-rays for stacked exposures and the very thick resist layers (hundreds to thousands of micrometers) of the LIGA' [German acronym for Lithographie, Galvanoplastie (electroforming), Abformung (molding)] process. Patterning of resists with thickness of hundreds to thousands of micrometers by deep X-ray lithography requires high contrast X-ray masks with thick absorber microstructures. Usually absorber patterns of deep X-ray lithography masks are fabricated by gold electroplating in trench-like microstructures made in a resist mold. A standard multi-step process for the fabrication of a deep X-ray mask for LIGA encompasses three steps, 1-3 or 1'-3:

- 1) UV proximity photolithography from a **W** mask first created by electron beam lithography (or laser beam patterning) to manufacture lower contrast 'soft' X-ray mask
- 1')- an alternative is to make the low contrast X-ray mask directly by electron beam lithography
- 2) deep X-ray lithographic copying from the intermediate X-ray mask onto a thick resist-coated substrate
- 3) gold electroplating from a liquid solution into thick resist (developed) proforma.

Because this is a serial process each step contributes to the total error budget. Depending on the tolerances of the final part, the tolerances on each of the step may result in multiple very expensive and time consuming operations. The principal domain of LIGA is the fabrication of parts with high accuracy and tight tolerances in thick material, such as those found in gear boxes for example, but the accuracy of the pattern definition of the absorbers on the masks set the tolerance limit for the 1:1 printing process. The optical pattern transfer process used for the traditional fabrication of LIGA masks by **W** contact printing restricts the tolerance or Critical Dimensions (CD) of masks to microns. As dimensions of components and microsystems decrease further into the sub-micrometer and nanometer regime higher resolution techniques are required for the fabrication of masks. **Further**, the relatively larger absorber height or higher aspect-ratio increases the difficulty of removal (or addition) of material.

There is also an important need to find rapid, convenient and economical methods for fast prototyping of microdevice products reducing turn-round time and cost in the initial development phase. A considerable effort is under way to find micromachining/microfabrication approaches for the rapid availability and low-cost fabrication of X-rays masks which is a critical element in commercialization of deep X-ray lithography and LIGA.

From a process point of view, the main difficulties in fabricating an X-ray mask are related to absorber formation as it combines high-aspect ratio, resolution and accuracy. **This** challenge is being exacerbated by the increase in structural height/depth of microsystems and sometimes simultaneously the decrease of lateral dimensions required of critical components requiring advanced fabrication techniques. Development time, process equipment, toxic materials and cost of manufacture are dramatically reduced. Mask changes are executed in a CAD file and no mask alignment is required for multiple level writing/machining.

Ion beam processes have benefited from a recrudescence of interest in the recent years. Since the scattering of ions once absorbed is minimum compared with that of electrons and photons, ion lithography through a mask, in particular with a reductive projection system is considered a contender in the next generation of advanced lithographic methods for high resolution patterning. The use of Focused Ion Beam (FIB) has also advantages over other microfabrication methods, especially as a resistless and maskless technology. A growing trend is to use FIB not only in its traditional electronics applications from test devices, characterization failure analysis, repair and repair to modification of integrated circuits to lithographic mask repair. More recently it was used as a 3D micromachining technique in other fields such as manufacture of micro-gears², surgical instruments³, micro-tooling⁴, micro-optical elements'. **FIB** systems and FIB based process are emerging as powerful and very versatile tools for the machining and precision

prototyping in the micron and sub-micron range^{5,6}. Many novel applications in MEMS micro-tooling are being addressed^{7,8} and, more recently has expanded to the direct writing of three-dimensional structures at both the microscopic and nanoscopic level

The work reported here emphasizes the use of chemically-assisted focused ion beam etching as a tool for the manufacture of high-aspect-ratio gold microstructures for deep X-ray masks. An example of the three-dimensional FIB etching of diamond in the microscopic and nanoscopic domains.

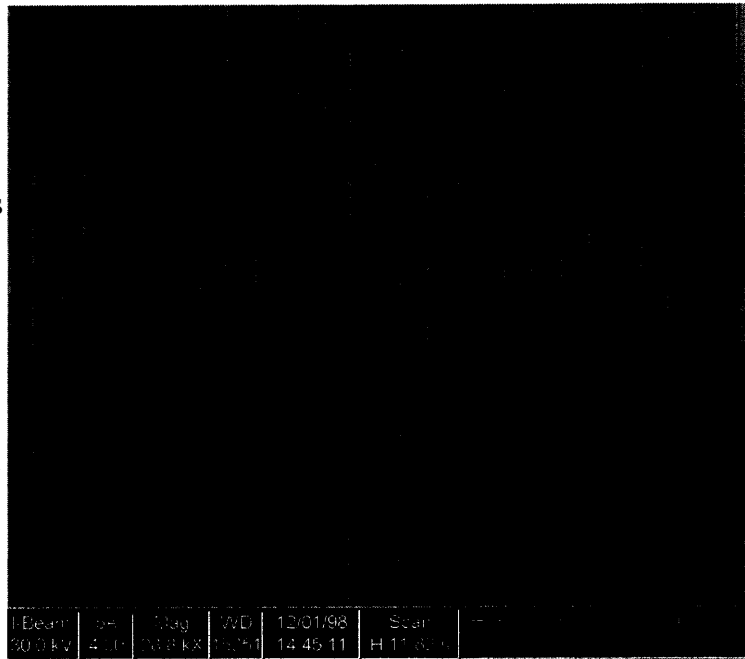


Figure 1. Grating of 22 nm width lines milled directly in 0.9 μm of Au.

2. Experimental procedure and results

The rate of material erosion by the ion beam depends on the dwell time, beam current and presence of reactive gas. The beam current defines the spot size of the beam which in turn defines resolution and feature size. For FIB micromachining the aspect ratio is limited by the redeposition of sputtered material on the surfaces of the structures. The redeposition problem can be alleviated by using a Gas Injection System (GIS) locally injecting on the substrate an appropriate gas that forms volatile by-products that are removed by ultra-high vacuum. Such chemically-assisted etching⁵ increases the verticality of walls expanding micromachining applications to those requiring high aspect ratio, extreme anisotropic and high-speed erosion processes. This is achieved without the sacrifice of feature size or the accuracy of the process.

— 100 nm

Figure 2. Grating of ~20 nm width lines milled directly in 3.5 μm of Au.

The FEI (FIB200-THP) system used in this work is equipped with a Gallium liquid metal ion source operating at 30 keV and a localized Iodine Gas Injection System (GIS) system in an ultra-high vacuum environment. In preliminary demonstrations of this fabrication technique 22 nm width lines were milled directly in a vector scan mode through 0.9 micron thick gold to form absorber structures on X-ray masks³ (Figure 1). A reactive iodine atmosphere was locally introduced onto the substrate with a small diameter needle positioned close to the sample surface. In fabricating 20-nanometer wide x 400-micron long x 3.5-micron deep trenches in a gold absorber (Figure 2 - hole FIB cut through 200 μm Si substrate) the addition of the iodine increased the milling rate by a factor 25: from 1.8 seconds to 0.07 seconds.



Figure 3. Diamond 3D nano-sculptured structure

FIB direct removal methods can create more complex structures such as the fabrication of "gray-scale" masks with a variation of thickness/sloped absorber pattern structures'. Pattern transfer can then amplify these topographical variations with X-ray printing, allowing for the fabrication of three-dimensional structures⁸.

FIB milling can be extended further to the direct micro-tooling of three-dimensional microscopic or nanoscopic scaled that might represent a 3D mold rather than a mask. The first image in Figure 3 presents the "arm" stalk directly milled out of the rough diamond (fixed to quartz tube) with a 550 nm diameter (10,000 pA) beam, the more neatly tapered "arm" was milled with 310 nm (1000 pA) beam and the image of the hand was created by milling using rectangular patterns in various views with 120 nm (10 pA) beam. The wrinkles, creases and rounded forms of the palm were formed with a 20 nm (1 pA) beam of lines and circular patterns.

3. Discussion

Ion beam processes have benefited from a resurgence of interest in the recent years^{9,10}. Since the scattering of ions once absorbed is minimum compared with that of electrons and photons, ion lithography through a mask, in particular with a reductive projection system is considered a contender in the next generation of advanced lithographic methods for high resolution patterning. The use of FIB has also advantages over other microfabrication methods, especially as a resistless and maskless technology. A growing trend is to use FIB not only in its traditional electronics applications from test devices, characterization failure analysis, repair and

modification of integrated circuits to lithographic mask repair". More recently it was used as a 3D micromachining technique in other fields such as manufacture of micro-gears², surgical instruments³, **micro-tooling**⁴, micro-optical elements^{5,6}.

Direct removal methods of etching or milling are very versatile and can lead to a considerable simplification of the process as the pattern structures are formed in a single step. The capability of Focused Ion Beam (FIB)-based systems to undertake direct and highly anisotropic erosion of thin and thick gold coatings provides a new level of flexibility and simplicity by simplifying dramatically the process of absorber formation for X-ray masks. In particular, it eliminates the steps of the conventional lithographic process of resist deposition, resist development, electroplating and resist removal. It also eliminates various problems associated with absorber formation by electroplating such as debonding of resist in the plating solution during long plating time that leads to the underplating of the structures, variations of absorber thickness as a function of the pattern area being plated, defects related to non-uniformity of deposition of material from the liquid phase, density variation of the deposited material, etc. It also clearly reduces development time and cost of manufacturing.

Besides the simplification and speed of execution, the main advantages of the gas-assisted FIB etching technique are:

- Very localized etching or deposition
- Wide range of lateral dimensions : nanometer, submicronic, micronic, millimeter
- Etching depth from a few nanometers to millimeters
- High aspect ratios (> 100) through the avoidance of redeposition of sputtered materials during the process by combining a reactive atmosphere with ion beam
- Very high precision both laterally and in-depth, therefore capability of 3D-patterning for 3D and gray lithography using the variation of thickness/sloped structures of the absorber pattern on the mask
- Suitability for rapid prototyping by making changes to a CAD file and for potentially testing multiple cases simultaneously
- A wide variety of materials that can be machined. Along with milling of various substrates, deposition of high Z elements from organo-metallic gas precursors has been developed
- Capability of multiple level writing/machining without mask aligner

At Norsam Technology, maskless ion-beam-assisted deposition from the organometallic gas precursors has been developed for various high Z elements, e.g.: Au⁹, W¹⁰. Gold is not used any longer in the fabrication of X-ray masks for shallow X-ray lithography (around 1 keV) of ultra-dense microelectronics where tungsten, tungsten alloys and particularly tantalum alloys are now the materials of choice. However, in deep X-ray lithography for LIGA applications Gold remains the absorber material of choice.

4. Conclusions

FIB micromachining appears useful for fabricating X-ray masks.

The rapid and direct rate of material removal makes gas assisted FIB applicable for rapid mask prototyping. The combination of extremely high resolution and fast direct-write and etching techniques provides a very powerful tool for the creation and repair of high-resolution X-ray masks. It also leads to the less arduous creation and repair of UV masks. The greatly simplified single step process is capable of the direct and rapid translation CAD defined templates into complex 3D mask structures with micronic, submicronic and nanometric dimensional breadth.

The chemically assisted focused ion beam etching of X-ray masks with CD of **20 nm** and aspect ratios of several hundreds represents an initial effort. Refinements of the technique are expected to reduce CD by a further factor of three (to ~ 7 nm) and increase aspect ratios accordingly.

The next step of the process development is to actually fabricate and test an X-ray mask made by FIB.

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